IS 5825 (1993): Test procedure for the determination of the temperature index of enamelled winding wires [ETD 33: Winding Wire]

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IS 5825 : 1993
IEC Pub 172 (1987)
(Reaffirmed 2003)

भारतीय मानक

इनैमलकृत वेष्टन तारों के सूचकांक को ज्ञात करने के लिए परीक्षण प्रक्रिया

(पहला पुनरीक्षण)

Indian Standard

TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED WINDING WIRES

(First Revision)

UDC 621·315·337·4 : 621·3·045·620·199

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March 1993 **Price Group 8**

Winding Wires Sectional Committee, ETD 33

NATIONAL FOREWORD

This Indian Standard, which is identical with IEC Pub 172 (1987) 'Test procedure for the determination of the temperature index of enamelled winding wires', issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Winding Wires Sectional Committee (ETD 33), and approval of the Electrotechnical Division Council.

This standard was first published in 1970. This revision has been made by adoption of IEC Pub 172 : 1987 to keep it in line with the IEC standard.

The text of IEC standard has been approved as suitable for publication as Indian Standard without deviations. Certain conventions are however not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker while in Indian Standards the current practice is to use point (.) as the decimal marker.

CROSS REFERENCE

In this Indian Standard, IEC Pub 216-1 (1987) 'Guide for the determination of thermal endurance properties of electrical insulating materials — Part 1 : General guidelines for ageing procedures and evaluation of test results' is referred to. Read in its place IS 8504 (Part 1) : 1977 'Guide for determination of thermal endurance properties of electrical insulating materials : Part 1 Temperature indices and thermal endurance profiles', which is equivalent to the IEC Publication.

The technical committee responsible for the preparation of this standard has reviewed the provisions of the IEC Pub 216-3 (1980) 'Guide for the determination of thermal endurance properties of electrical insulating materials — Part 3 : Statistical methods', referred to in this standard and has decided that it is acceptable for use in conjunction with this standard.

The technical committee clarified that in Item 5 'Test specimens', the wire metal and surface treatment of the wire will also effect the thermal life of the enamelled wire.

Only the English language text in the International Standard has been retained while adopting it in this standard.

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AMENDMENT NO. 1 AUGUST 2010
TO
IS 5825 : 1993 TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED WINDING WIRES

(*First Revision*)

Page 1

1 Scope

Replace the text of this clause by the following:

This test procedure specifies, in accordance with the provisions of IEC 60216-1, a method for evaluating the temperature index of enamelled and of tape wrapped round and rectangular wire. It does not include fibre-insulated wire or wire covered with tapes containing inorganic fibres.

2 Object

Replace the text of this clause by the following:

This test procedure is to determine the temperature index of enamelled and of tape-wrapped bare or enamelled, round and rectangular wire in air at atmospheric pressure by change in electric strength. The definition of the temperature index is in accordance with IEC 60216-1. The specimen is unvarnished or varnished with an impregnating agent. Testing varnished specimens will also evaluate the compatibility of the wire insulation with an impregnating agent. Thus the temperature indices of different combinations can be compared.

NOTE – The data obtained according to this test procedure provide the designer and development engineer with information for the selection of winding wire for further evaluation in insulation systems and equipment tests.

Page 2

3 Definitions of terms

Replace the first definition of this clause by the following:

Temperature index

The temperature index is a measure of relative thermal life and is the number, which corresponds to the temperature in degrees Celsius (°C) derived from the thermal endurance graph at 20 000 h, as calculated by equation 6 of annex A.

5.1 Preparation

Add, between the title and text of this subclause, the following title and note:

5.1.1 Enamelled round wire with a nominal conductor diameter of 0,800 mm up to and including 1,500 mm

NOTE – For round enamelled wire, in order to avoid undue fragility of the test specimen, experience has shown that nominal conductor diameters of 0,800 mm up to and including 1,500 mm are generally found convenient to handle and test.

Page 3

Add the following new subclause:

5.1.2 Tape wrapped round wire and enamelled or tape wrapped rectangular wire

NOTE – Any convenient dimension of round or rectangular wire may be used. However, for ease of forming, it is recommended that the dimensions be such that small bending forces can be used to shape the pieces required to prepare the specimen. Wire with high stiffness will yield specimens with poor wire-to-wire contact areas.

a) Two straight pieces of wire each of 250 mm length shall be cut from the supply spool.

b) 10 mm to 15 mm of the insulation shall be removed from one end of each piece of wire to provide for electrical connection.

c) Each piece shall be formed in a jig, as shown in figure 9. This produces a straight centre section of about 150 mm with bent ends, which provide the necessary flare at both ends of the final specimen.

d) The two formed pieces shall be placed together back-to-back and tightly wrapped with glass yarn over the straight centre section of the specimen, as shown in figure 10.

   Care shall be taken that the centre section shows a close contact between the two pieces. After tying, further bending of the ends shall be avoided. Pre-annealing of the specimen before testing or impregnating will remove stress and craze marks and therefore may be desirable with certain material.

e) Prior to testing the specimen shall be proof-tested at 1 000 V a.c.

5.2 Varnish impregnation

Replace the text of this subclause by the following:

Experience has shown that insulated wire according to IEC 60317 and impregnating agents according to IEC 60455-3-5 or IEC 60464-3-2 can affect one another during the thermal ageing process. Interaction between wire insulation and such agent may increase or decrease the relative thermal life of this combination compared with the life of the wire tested without impregnation. Therefore, with impregnated specimens, this test procedure may give an indication of the thermal endurance of a combination of wire insulation and impregnating agent.

If such impregnation is required, the following procedure shall be applied:

With the specimen in the vertical position, it shall be immersed in the impregnating agent for (60 ± 10) s (see note). It shall be removed slowly and uniformly at a rate of about 1 mm/s. It shall be drained horizontally for 10 min to 15 min and cured horizontally according to the manufacturer's recommendation or to an agreed schedule. If more than one treatment is to be given, immerse, drain and cure the specimen vertically reversing the specimen for each subsequent treatment.

NOTE – Some impregnating agents, such as high viscosity or thixotropic products may require alternative processing methods.

Page 4

5.3 Number of test specimens

Replace the second paragraph by the following:

Experience has shown that 21 specimens without impregnation and 11 specimens with impregnation give results with an acceptable tolerance. A minimum of 11 specimens shall be used.

5.4 Specimen holder

Insert, before the first paragraph, the following text:

5.4.1 For specimens according to 5.1.1

Add, after 5.4.1, the following new subclause:

5.4.2 For specimens according to 5.1.2

The specimen shall be hung in the oven. No special holder is required.

Page 5

7 Test voltage and its application

Replace, on page 6, the third paragraph of clause 7 by the following text:

The specimen is removed from the oven and allowed to cool to room temperature. A proof voltage is applied according to table 3 for specimens according to 5.1.1 and according to table 4 for specimens according to 5.1.2.

Page 6

Replace the title of table III by the following:

Table 3 – Proof voltage for round enamelled wire

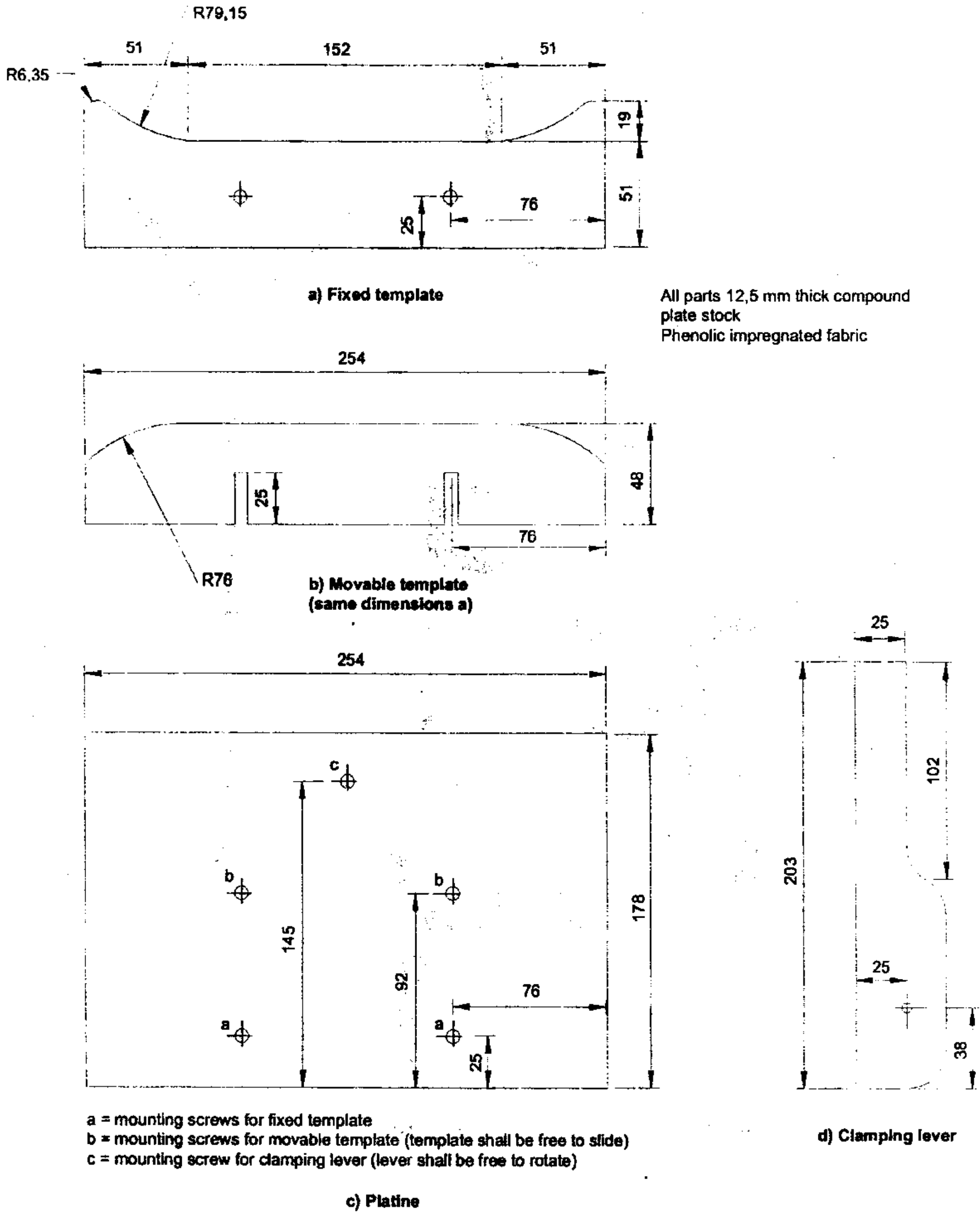
Add table 4 after table 3, as follows:

Table 4 – Proof voltage for tape-wrapped round and for enamelled or tape-wrapped rectangular wire

Increase in dimension due to the insulation mm		Voltage (r.m.s.)
Over	Up to and including	V
0,035	0,050	300
0,050	0,065	375
0,065	0,080	450
0,080	0,090	550
0,090	0,100	650
0,100	0,115	700
0,115	0,130	750
0,130	0,140	800
0,140	0,150	850

Page 13

Add, after figure 8, the following new figures 9 and 10:



Dimensions in millimetres

Figure 9 – Jig for bending large magnet wire, dielectric test specimen

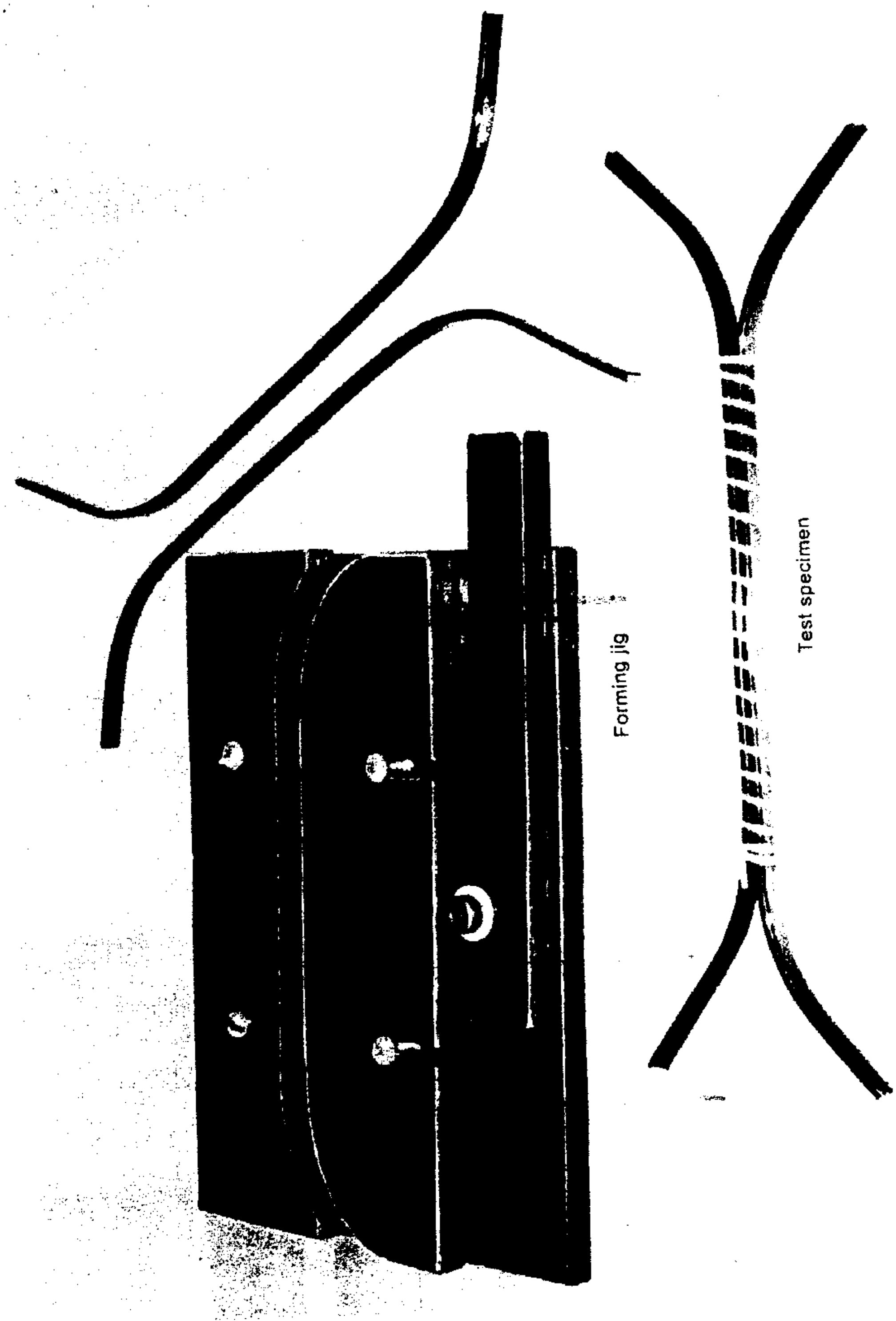


Figure 10 – Forming jig and test specimen

Page 14

Replace the title of appendix A by the following:

Annex A
(normative)

Method for calculation of the regression line

Page 19

Replace the text of appendix B by the following:

Annex B
(normative)

Correlation coefficient

The correlation coefficient r is a measure of the amount of relationship between variables.

When r = 1, a perfect correlation between the variables exists, when r = 0, a completely random relation exists. The correlation coefficient shall be calculated as follows:

$$r = \frac{N\Sigma XY - (\Sigma X)(\Sigma Y)}{\sqrt{\left[N\Sigma X^2 - (\Sigma X)^2\right]\left[N\Sigma Y^2 - (\Sigma Y)^2\right]}}$$

with X, Y, N, as in annex A.

The correlation coefficient of the sample calculation according to table AII in annex A is r = 0,996.

(ETD 33)

Indian Standard

TEST PROCEDURE FOR THE DETERMINATION OF THE TEMPERATURE INDEX OF ENAMELLED WINDING WIRES

(First Revision)

1. Scope

This test procedure specifies, in accordance with the provisions of IEC Publication 216-1, a method for evaluating the temperature index of round enamelled winding wires. It is not applicable to rectangular winding wires or to fibre-insulated winding wires.

In order to avoid undue fragility of the test specimens, experience has shown that sizes from 0.8 mm to 1.5 mm are generally found convenient to handle and test.

2. Object

This test procedure is to determine the thermal endurance of enamelled round wires in air at atmospheric pressure. The thermal endurance, characterized by Temperature Index, is specified in most performance specifications for enamelled wires. The data obtained on the long-term characteristics of enamelled winding wires also provide the designer and development engineer with information for the selection of winding wire for further evaluation in insulation systems and equipment tests.

This test procedure covers only the evaluation of thermal endurance by changes in electric strength; to evaluate the changes of other properties, further test procedures are needed.

Exposure of some types of enamelled wire to heat in gaseous or liquid environments in the absence of air may give thermal endurance characteristics different from those obtained in air. This fact shall be considered when interpreting the results obtained by heating in air with respect to applications where the wire will not be exposed to air in service. Sizes other than those specified in Clause 15 of the relevant specification sheet dealing with thermal endurance may give different thermal endurance characteristics. The conductor material in contact with the enamel insulation may affect the thermal endurance characteristics.

The suitability or compatibility of an insulating varnish with enamel insulation can also be tested and temperature indices of combinations can be compared by using this method.

Electric stress applied for extended periods at a level exceeding or even approaching the discharge inception voltage may significantly change the thermal endurance of enamelled winding wires, varnished or unvarnished. Under such electric stress conditions, comparisons between materials may also differ from those developed using this method.

It should be made clear that the Temperature Index determined by this method is the number corresponding to the temperature in degrees Celsius at which the regression line

intersects the 20 000 h line. The temperature in degrees Celsius corresponding to the Temperature Index is not necessarily that at which the wire is recommended to be operated. This depends on many factors, including the type of equipment involved.

Environmental factors such as moisture, chemical contamination, and mechanical stresses or vibrations, are factors that may result in failure after the enamelled wire has been weakened by thermal deterioration and are more appropriately evaluated in insulation system tests.

3. Definition of terms

Temperature Index

The number corresponding to the temperature in degrees Celsius derived from the thermal endurance graph at 20 000 h as calculated by equation (6) of Appendix A.

Specimen failure time

The hours at the exposure temperature that have resulted in a specimen failing the proof test (see Sub-clause 8.1).

Time to failure

The hours to failure calculated from the specimen failure times for a set of specimens at one exposure temperature in accordance with Sub-clause 8.2.

4. Summary of procedure

A set of specimens in accordance with Clause 5 is subjected to a testing cycle. This cycle consists of a heat-storing period at a temperature given in Clause 6, followed by a proof voltage test at room temperature in accordance with Clause 7.

This cycle is repeated until a sufficient number of specimens has failed, and the time to failure is calculated in accordance with Clause 8. The test is carried out at three or more temperatures. A regression line is calculated in accordance with Sub-clause 8.4 and the time to failure values plotted on thermal endurance graph paper as a function of the exposure temperature.

The temperature, in degrees Celsius, corresponding to the point of intersection of the regression line with the ordinate of 20 000 h endurance represents the Temperature Index of the winding wire under test.

5. Test specimens

5.1 *Preparation*

a) A piece of wire approximately 400 mm in length shall be twisted together over a distance of 125 mm with a device as shown in Figure 1. The force (weight) applied to the wire pair while being twisted and the number of twists are given in Table I.

TABLE I

Force and number of twists for specimens

Nominal diameter (mm)		Force applied to wire pairs (N)	Number of twists per 125 mm
Over	Up to and including		
0.10	0.25	0.85	33
0.25	0.35	1.70	23
0.35	0.50	3.40	16
0.50	0.75	7.00	12
0.75	1.05	13.50	8
1.05	1.50	27.00	6
1.50	2.15	54.00	4
2.15	3.50	108.00	3

b) Spacers may be prepared as shown in Figure 2. Such thermally stable insulating materials as ceramic or silicone glass fibre laminate may be used. The spacers are marked with a suitable identifying letter or number.

c) The test specimens may be shaped in a jig, an engineering drawing of which is shown in Figure 3. A specimen is placed in the jig and a spacer, placed on the parallel leads of the twisted pair, is brought up to the face of the jig as shown in Figure 4. The leads are then bent parallel to hold the spacer in position. The forming jig provides more uniform test specimens. If a specimen holder is used, the spacers are unnecessary.

d) The loop at the end of the twisted section shall be cut at two places (not one) to provide the maximum spacing between the cut ends as shown in Figure 5. Any bending of the wires, at this end or the other untwisted end, to ensure adequate separation between the wires shall avoid sharp bends or damage to the insulation.

e) In order to ensure homogeneity of the batch of test specimens, it is recommended that test specimens be subjected to a test voltage three times the value given in Table III for a period of 1 s.

5.2 *Varnish impregnation*

Experience has shown that enamelled wire and electrical insulating varnishes or resins can affect one another during the thermal ageing process. Interaction between varnish or resin and enamel may increase or decrease the relative thermal life of the varnish and enamelled wire combination compared with the life of the enamelled wire tested without varnish. This test procedure may give indications on the thermal endurance of a combination of insulating varnish or resin and enamelled wire.

The varnish should be diluted with a suitable solvent to obtain the required coating thickness. The twisted specimens are dipped to the depth to cover the spacer for not less than 30 s, then slowly withdrawn at a uniform rate of approximately 100 mm/min. The specimens are then cured for the time and at the temperature recommended by the varnish manufacturer. If the application requires it, or specific comparisons are being made between varnishes, the specimens should be reverse dipped and cured in the opposite direction. The varnishes considered shall be individually diluted in such a manner as to provide the same coating thickness. It has been noted that two applications of varnish, reverse dipped and cured, provide a more uniform coating and more consistent data.

5.3 *Number of test specimens*

The accuracy of the test results depends largely upon the number of test specimens aged at each temperature. A greater number of test specimens is required to achieve an acceptable degree of accuracy if there is a wide spread in results among the specimens exposed at each temperature.

Experience has shown that 21 test specimens usually give an acceptable average endurance. A minimum of 11 specimens shall be used.

5.4 *Specimen holder*

It has been found that individual handling of the twisted specimens may introduce premature failures. It is, therefore, recommended that the specimens be placed in a suitable holder, as shown in Figure 6. The holder should be designed in a manner that will protect the twisted specimens from external mechanical damage and warpage. The holder will be so constructed as to allow the ends of the twist to protrude from the holder to make electrical connection for the proof testing as shown in Figure 7. The holder should be designed for at least 11 specimens to decrease handling time.

6. Temperature exposure

Recommended temperatures to which the test specimens are subjected are given in this clause.

In Table II, the recommended temperature and time of exposure in each cycle are given. A test cycle consists of exposure to a high temperature and testing at room temperature (20 °C to 30 °C). The test specimens shall be placed directly into and removed from the ageing ovens without controlling the heating or cooling rate.

The ovens should be heated to the proper temperature before the specimens are subjected to the exposure temperature.

The specimens should be aged in a forced air circulation oven which is capable of maintaining the temperature of the specimens under test within 2 °C of the selected exposure temperature.

The exposure times are selected to subject the test specimens to approximately 10 cycles at each temperature before the time to failure is reached.

Thermal endurance values obtained from test specimens subjected to an average of less than eight or more than twenty cycles at the exposed temperature may not be reliable and should not be used to predict the temperature rating of the enamelled wire. A shorter or longer cycle time than those given in the table may, therefore, be chosen for certain exposure temperatures, to ensure that the average number of cycles to failure falls within this range.

After the specimens have been subjected to a particular cycle, the time may be appropriately increased or decreased to control the number of cycles required to reach the time to failure.

Test specimens should be exposed to a minimum of three and preferably four exposure temperatures. The lowest exposure temperature should be one which results in a time to failure of more than 5000 h. An exposure temperature which results in values of less than 100 h is

generally considered too high. Exposure temperatures should be not more than 20 °C apart. The accuracy of the temperature index predicted from the results will increase as the exposure temperature approaches the temperature to which the insulation is exposed in service. The lowest exposure temperature shall be not more than 25 °C above the anticipated Temperature Index for the enamelled wire.

TABLE II

Recommended exposure times in days per cycle *

Exposure or ageing temperature (°C)	Estimated temperature index						
	105–109	120–130	150–159	180–189	200–209	220–229	240–249
320							1
310							2
300						1	4
290						2	7
280					1	4	14
270					2	7	28
260				1	4	14	49
250				2	7	28	
240				4	14	49	
230			1	7	28		
220			2	14	49		
210		1	4	28			
200		2	7	49			
190	1	4	14				
180	2	7	28				
170	4	14	49				
160	7	28					
150	14	49					
140	28						
130	49						
120							

* A cycle consists of one ageing period followed by one proof-voltage test.
The recommendations in Table II differ from those in IEC Publication 216 but have been found more suitable for enamelled wires.

7. Test voltage and its application

The voltage to be applied shall be an a.c. voltage and have a nominal frequency of 50 Hz or 60 Hz of an approximately sine-wave form, the peak factor being within the limits of $\sqrt{2} \pm 5\%$ (1.34 to 1.48). The test transformer shall have a rated power of at least 500 VA and shall provide a current of essentially undistorted waveform under test conditions.

To detect failure, the overcurrent device shall operate when a current of 5 mA or more flows in the high-voltage circuit. The test voltage source shall have a capacity to supply the detection current (5 mA or more) with a maximum voltage drop of 10%.

The test specimens are removed from the ovens and cooled to room temperature. Each specimen is subjected to a proof voltage according to the average thickness of the enamel, as specified in Table III.

TABLE III

Proof voltage

Increase in diameter due to the insulation (mm)		Voltage (r. m. s.) (V)
Over	Up to and including	
	0.015	300
0.015	0.024	300
0.024	0.035	400
0.035	0.050	500
0.050	0.070	700
0.070	0.090	1 000
0.090	0.130	1 200

The proof voltage shall be applied to the test specimens for approximately 1 s. A relatively short time of application of the test voltage is desirable to minimize the effects of corona and dielectric fatigue.

Care must be taken in all cases to avoid mechanical damaging of the test specimens. The specimens that fail the proof test are discarded and the remaining specimens returned to the oven for another temperature exposure.

8. Calculations

8.1 *Specimen failure time*

The failure time of an individual specimen at one exposure temperature is determined by calculating the mid-point between the total hours of exposure temperature at which the specimen failed the proof voltage and the total hours of exposure of the previous cycles. This assumes that the specimen would probably have failed the proof voltage somewhere in the middle of the last temperature exposure cycle. Thus, the specimen failure time is the sum of the total hours at the time to failure, minus half the hours of the last exposure cycle.

8.2 *Time to failure*

The time to failure of a set of specimens at one exposure temperature may be calculated by using either the median value or the logarithmic mean value. For many materials, the median value is statistically valid. In most cases, the use of the median will significantly reduce testing time, since the test ceases once the median value has been obtained.

When using the median value, the time to failure is calculated as follows:

If there is a total number of n specimens in a set of specimens, then the time to failure of the set:

a) equals the specimen failure time of specimen number $(n+1)/2$ if n is odd (see Sub-clause 8.1);

b) equals the mean value of the specimen failure times of specimens number $n/2$ and $(n+2)/2$, if n is even (see Sub-clause 8.1).

For instance, if n is 12, the time to failure of the set would be the mean value of the specimen failure times of the sixth and the seventh specimen. For convenience, it is suggested that, when the median value is used for calculating the time to failure of the set, the total number of specimens of a set be odd, thus simplifying calculation.

When using the mean value, the time to failure is calculated by dividing the sum of the logarithms of the specimen failure times of the set (see Sub-clause 8.1) by the total number n of specimens in the set. The antilogarithm of this mean value is the time to failure of the set.

8.3 *Linearity of data*

To avoid misleading extrapolations (see Sub-clause 8.4), the correlation coefficient should be calculated as given in Appendix B, to provide a measure of linearity.

If the correlation coefficient r is equal to or greater than 0.95, the data is said to be linear and the data points will be reasonably close to a straight line. In the event that the correlation coefficient is less than 0.95, the data is said to be non-linear and an additional test should be made at a temperature below the lowest previous temperature.

The new temperature point may be 10 °C below the previous lowest temperature point. When re-calculating the Temperature Index and correlation coefficient, one temperature point may be deleted, starting with the highest temperature, for each new temperature point obtained.

The data will be linear if the thermal deterioration of the enamelled wire or the varnished enamelled wire appears as one chemical reaction. Non-linearity may indicate that:

a) two or more reactions which have different activation energies (slopes) are predominant at different temperatures within the testing range: or

b) that errors have been introduced through the sampling technique and/or the testing procedure.

Non-linear data should not be used for extrapolation.

8.4 *Calculating and plotting thermal endurance and Temperature Index*

Thermal endurance is graphically presented by plotting the time to failure (see Sub-clause 8.2) versus its respective exposure temperature on graph paper having a logarithmic time scale as the ordinate and the reciprocal of absolute temperature as the abscissa. The exposure temperatures at 2 000 h and 20 000 h are estimated based on the

first order regression calculation presented in Appendix A. A regression line is drawn through these two points on the graph, which represents the thermal endurance of the enamelled winding wire (see Figure 8).

The Temperature Index of the enamelled wire is the number corresponding to the temperature in degrees Celsius at which the regression line intersects the 20 000 h line. It is listed without reference to degrees Celsius.

If further statistical analysis of the data is necessary, reference may be made to IEC Publication 216-3.

9. Report

The report of the results shall contain the following information:

1) Identification or description of the wire enamel, grade and the type of conductor (e.g. copper, aluminium, etc.).

2) Identification or description of the impregnating varnish and varnishing process.

3) Time to failure of each set of specimens at each exposure temperature.

4) A graph of the first order regression line through the time to failure values.

5) The Temperature Index (T.I.).

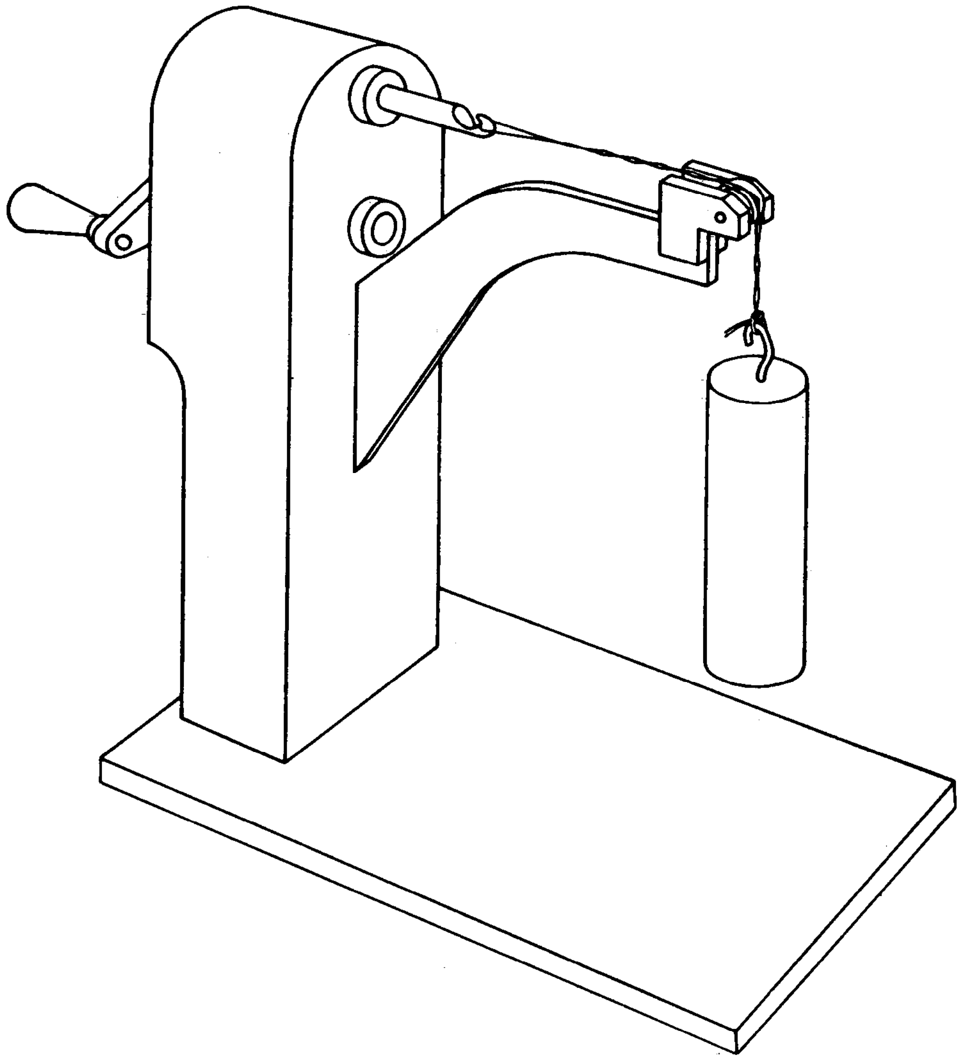
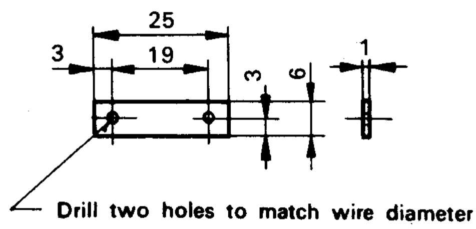


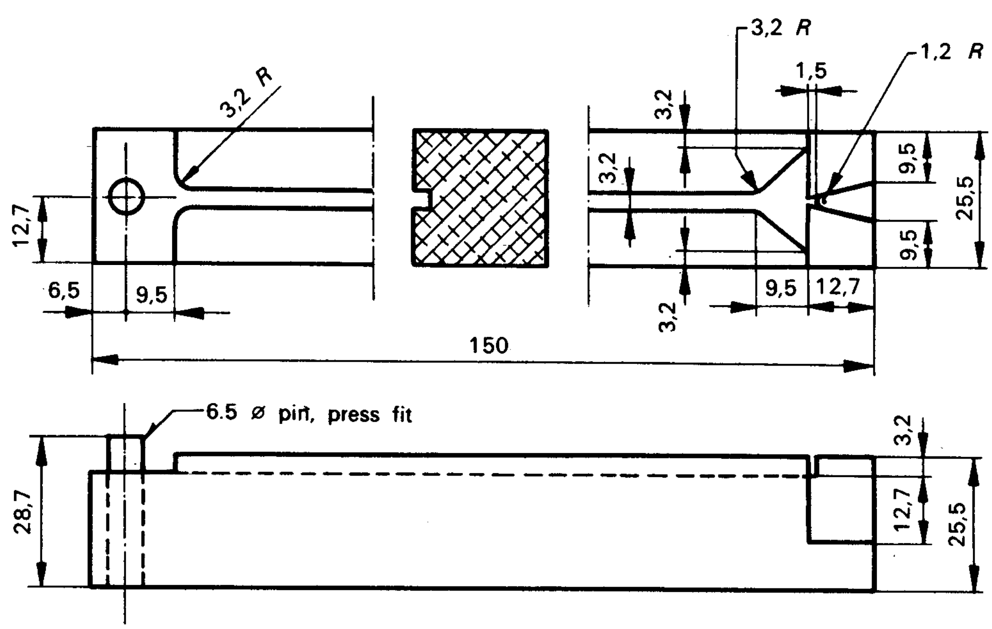
FIG. 1. — Device used to form test specimen.

Dimensions in millimetres



Material: silicone glass laminate

FIG. 2. — Spacer.



Note. — Round all corners in jig slot as shown.

184/81

Material: aluminium

FIG. 3. — Twist forming jig.

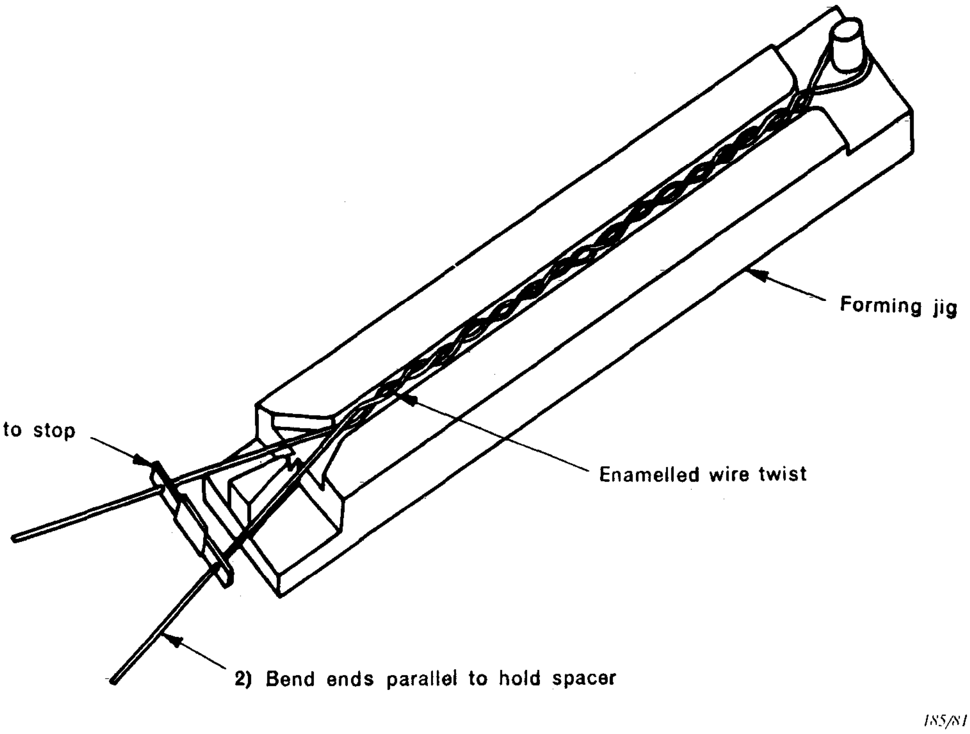


FIG. 4. — Test specimen set up in forming jig.

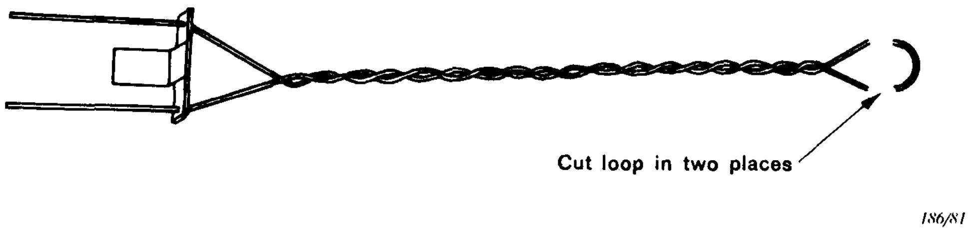
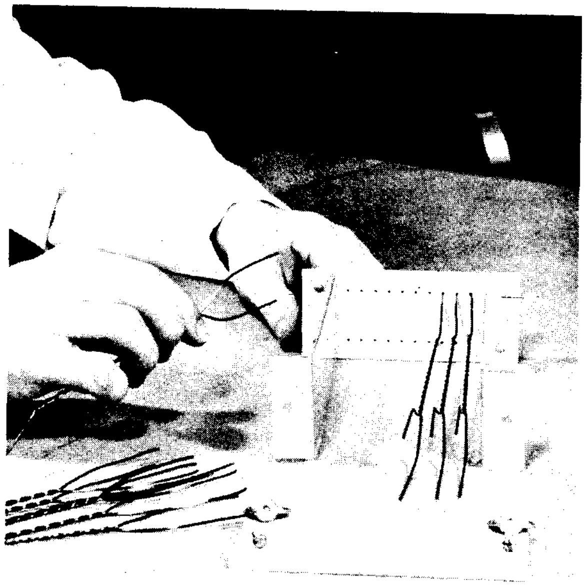
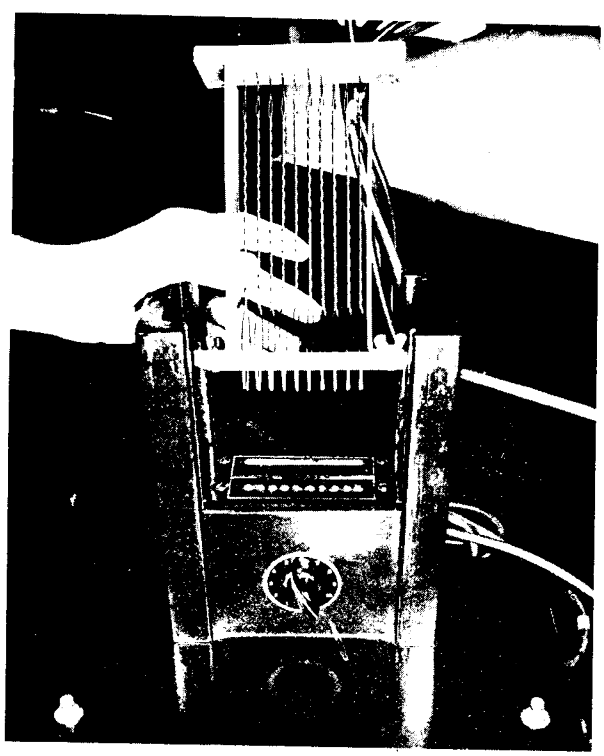


FIG. 5. — Test specimen formed with loop cut.



534/81

FIG. 6. — Specimen holder.



535/81

FIG. 7. — Specimen holder.

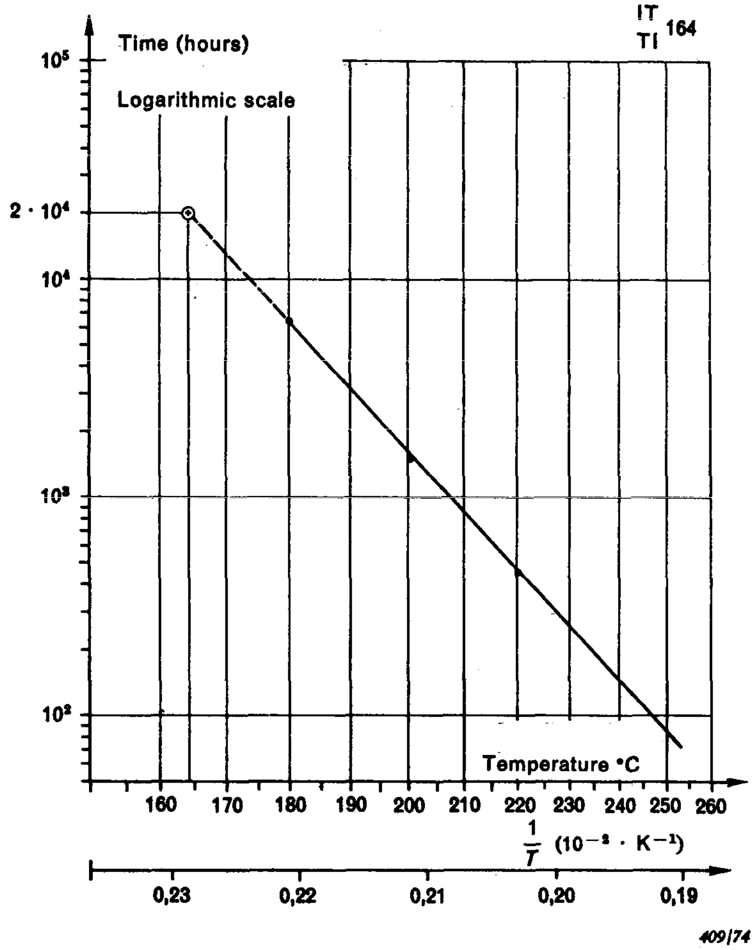


FIG. 8. — Thermal endurance graph Temperature Index.

APPENDIX A

SIMPLIFIED METHOD FOR CALCULATION OF THE REGRESSION LINE

The purpose of this Appendix is to present a method for quickly plotting the regression line for the endurance data. This method may be used for any number of measurements at various test temperatures. If information concerning the confidence limits is required, it is suggested that a more detailed analysis be made in accordance with IEC Publication 216-3.

It has been established that many insulations deteriorate in such a manner that the following equation applies:

$$L = A e^{B/T} \tag{1}$$

where:

L = insulation endurance in hours
T = absolute temperature in kelvins
A, B = constants for each insulation, and
e = base of natural logarithms

Equation (1) may be expressed as a linear function by taking logarithms:

$$\log_{10} L = \log_{10} A + (\log_{10} e) \cdot \frac{B}{T} \tag{2}$$

Let:

$Y = \log_{10} L$
$a = \log_{10} A$
$X = 1/T$
$b = (\log_{10} e) \cdot B$

Then:

$$Y = a + bX \tag{3}$$

Thus, data from testing at higher temperatures may be plotted on $\log_{10} L$ versus $1/T$ graph paper and a straight line extrapolated to lower temperatures. However, since the nature of logarithmic plots does not allow accurate extrapolation by the method of drawing the best apparent straight line through the data points, a more rigorous method must be used for greater accuracy and uniformity. By using the method of least squares, the constants a and b may be derived in terms of the experimental data obtained. These equations are as follows:

$$a = \frac{\Sigma Y - b \Sigma X}{N} \tag{4}$$

$$b = \frac{N \Sigma XY - \Sigma X \Sigma Y}{N \Sigma X^2 - (\Sigma X)^2} \tag{5}$$

where:

$X = 1/T$ = reciprocal of the test temperature in kelvins (θ °C + 273)
N = number of times to failure
$Y = \log_{10} L$ = logarithm of time to failure
Σ = summation of N values.

Knowing the constant a and the slope b of the regression line, the temperature at any required life value may be calculated as follows:

$$Y = a+bX \tag{3}$$

$$T = \frac{1}{X} = \frac{b}{Y-a} \tag{3a}$$

Temperature at 20000 h in degrees Celsius (Temperature Index) $= \dfrac{b}{4.3010-a} - 273$ (6)

Temperature at 2000 h in degrees Celsius $= \dfrac{b}{3.3010-a} - 273$ (7)

To simplify the handling of the test data used in Equations (4) to (7), it is suggested that the steps for a sample calculation be followed as outlined below (see Tables AI and AII):

1) Under (°C) as illustrated in Table AII, list each temperature at which a set of specimens was tested.

2) In the second and third columns, list the reciprocals ($X = 1/T$) and the reciprocals squared ($X^2 = 1/T^2$) of the above test temperatures converted to kelvins (see also Table AI).

3) In the fourth column, list the time to failure L, in hours, of each set of specimens, and in the fifth column, list the $\log_{10}$ of the values in the fourth column ($Y = \log_{10}L$).

4) In the sixth column, list the products of X and Y.

5) Provide summation for columns 2, 3, 5 and 6 and enter the summation (indicated by Σ) at the bottom of the respective column.

6) Indicate the number N of times to failure on the worksheet.

7) Using the values obtained in steps 5 and 6, compute b (Equation 5) and a (Equation 4) in that order. The constant a will always be negative.

8) Using constants a and b, calculate the temperature in degrees Celsius at 20000 h (Equation 6) and at 2000 h (Equation 7).

9) Plot the above two temperature points from step 8 on $\log_{10}L$ versus $1/T$ graph paper and draw the regression line through them.

10) Plot the times to failure L at their respective temperatures on the same graph.

TABLE AI

Commonly used test temperatures in degrees Celsius and the corresponding kelvins with its reciprocal and reciprocal squared values (see Table AII)

θ, °C	T, K	$X = 1/T$, K^{-1}	$X^2 = 1/T^2$, K^{-2}
105	378	$2.645\,50 \times 10^{-3}$	$6.998\,68 \times 10^{-6}$
125	398	$2.512\,56 \times 10^{-3}$	$6.312\,97 \times 10^{-6}$
130	403	$2.481\,39 \times 10^{-3}$	$6.157\,29 \times 10^{-6}$
140	413	$2.421\,31 \times 10^{-3}$	$5.862\,73 \times 10^{-6}$
150	423	$2.364\,07 \times 10^{-3}$	$5.588\,81 \times 10^{-6}$
165	438	$2.283\,11 \times 10^{-3}$	$5.212\,57 \times 10^{-6}$
175	448	$2.232\,14 \times 10^{-3}$	$4.982\,46 \times 10^{-6}$
180	453	$2.207\,51 \times 10^{-3}$	$4.873\,08 \times 10^{-6}$
185	458	$2.183\,41 \times 10^{-3}$	$4.767\,26 \times 10^{-6}$
190	463	$2.159\,83 \times 10^{-3}$	$4.664\,85 \times 10^{-6}$
200	473	$2.114\,16 \times 10^{-3}$	$4.469\,69 \times 10^{-6}$
220	493	$2.028\,40 \times 10^{-3}$	$4.114\,40 \times 10^{-6}$
225	498	$2.008\,03 \times 10^{-3}$	$4.032\,19 \times 10^{-6}$
240	513	$1.949\,32 \times 10^{-3}$	$3.799\,84 \times 10^{-6}$
250	523	$1.912\,05 \times 10^{-3}$	$3.655\,92 \times 10^{-6}$
260	533	$1.876\,17 \times 10^{-3}$	$3.520\,02 \times 10^{-6}$
280	553	$1.808\,32 \times 10^{-3}$	$3.270\,01 \times 10^{-6}$
300	573	$1.745\,20 \times 10^{-3}$	$3.045\,73 \times 10^{-6}$
320	593	$1.686\,34 \times 10^{-3}$	$2.843\,74 \times 10^{-6}$

TABLE AII

Sample calculation

Temperature (°C)	$X = 1/T$	$X^2 = 1/T^2$	L (h)	$Y = \log_{10}L$	$XY = (\log_{10}L)/T$
170	$2{,}257\,73 \times 10^{-3}$	$5{,}095\,57 \times 10^{-6}$	5 600	3,748 19	$8{,}460\,92 \times 10^{-3}$
185	$2{,}183\,41 \times 10^{-3}$	$4{,}767\,26 \times 10^{-6}$	2 600	3,414 97	$7{,}456\,27 \times 10^{-3}$
200	$2{,}114\,16 \times 10^{-3}$	$4{,}469\,69 \times 10^{-6}$	1 500	3,176 09	$6{,}714\,78 \times 10^{-3}$
215	$2{,}049\,18 \times 10^{-3}$	$4{,}199\,14 \times 10^{-6}$	640	2,806 18	$5{,}750\,37 \times 10^{-3}$
Σ	$8{,}604\,09 \times 10^{-3}$	$18{,}531\,66 \times 10^{-6}$		13,145 43	$28{,}382\,34 \times 10^{-3}$

$N = 4$

$$b = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2} = \frac{4 \times 28{,}382\,34 \times 10^{-3} - 8{,}604\,09 \times 10^{-3} \times 13{,}145\,43}{4 \times 18{,}531\,66 \times 10^{-6} - 8{,}604\,09 \times 10^{-3} \times 8{,}604\,09 \times 10^{-3}} = 4\,413$$

$$a = \frac{\Sigma Y - b\Sigma X}{N} = \frac{13{,}145\,43 - 4\,413 \times 8{,}604\,09 \times 10^{-3}}{4} = -6{,}206\,10$$

Temperature at 20 000 h in degrees Celsius $= \dfrac{b}{Y-a} - 273$

$$= \frac{4\,413}{4{,}301\,0 + 6{,}206\,10} - 273 = 147\ °\text{C}$$

Temperature at 2 000 h in degrees Celsius $= \dfrac{b}{Y-a} - 273$

$$= \frac{4\,413}{3{,}301\,0 + 6{,}206\,10} - 273 = 191\ °\text{C}$$

This graph should contain all appropriate information regarding insulating materials and systems.

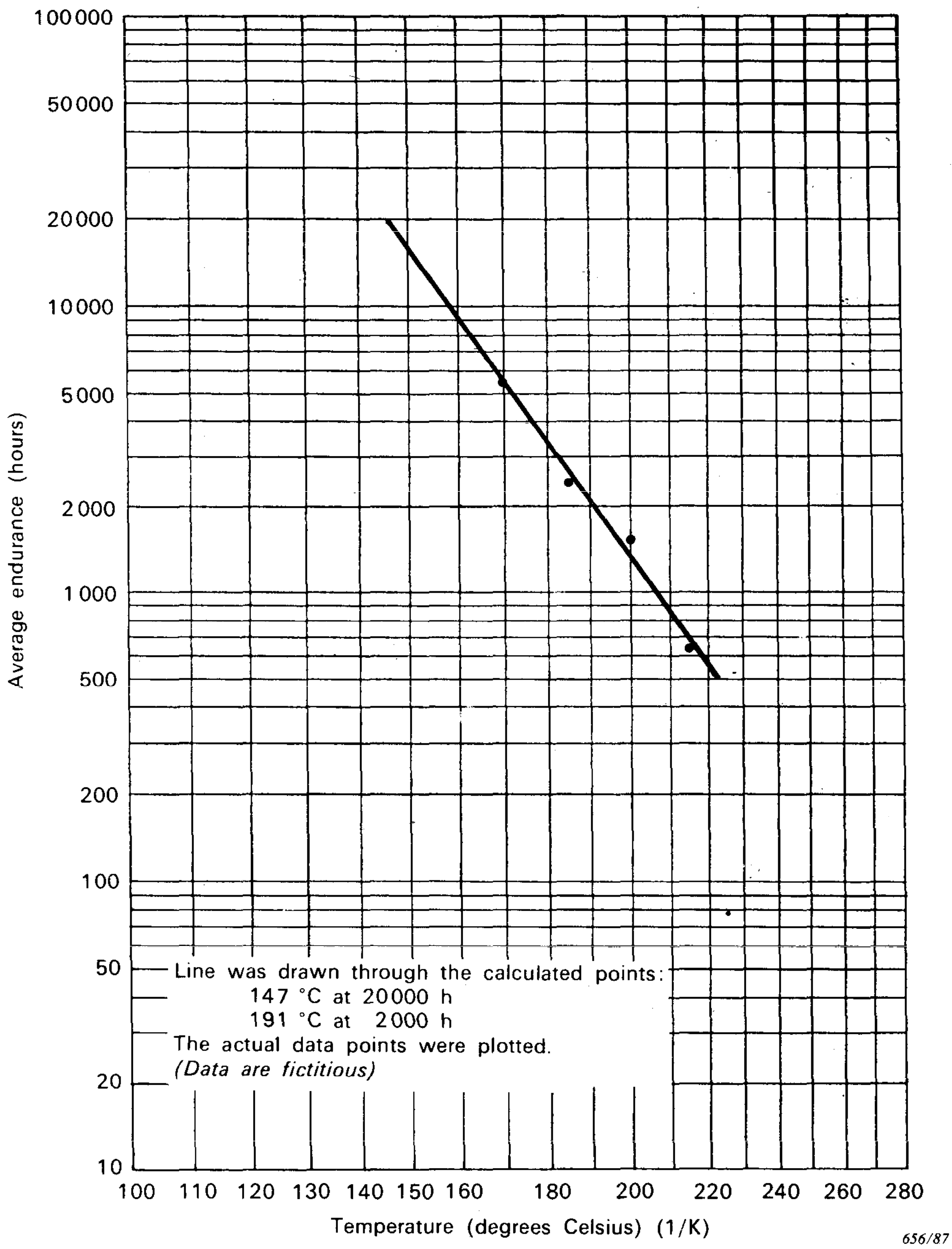


FIG. AI. — Plot of regression line based on sample calculation (Table AII).

APPENDIX B

CORRELATION COEFFICIENT

The correlation coefficient r is a measure of the amount of relationship between variables. When $r = 1.0$, a perfect association between the variable exists, and when $r = 0$, a completely random relation exists.

$$\left.\begin{aligned} N &= \text{number of occurrences} \\ X, Y &= \text{the variables} \end{aligned}\right\} \text{see Appendix A}$$

$$r = \frac{N\Sigma XY - (\Sigma X)(\Sigma Y)}{\sqrt{[N\Sigma X^2 - (\Sigma X)^2][N\Sigma Y^2 - (\Sigma Y)^2]}}$$

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